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# Principles of Corrosion and Corrosion Monitoring

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# PRINCIPLES OF CORROSION AND CORROSION MONITORING

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## ABSTRACT

Corrosion is a complex electro-chemical phenomenon that can not be eliminated but can normally be controlled in a cost-effective manner. Recent amendments to the National Interim Primary Drinking Water Regulations deal with corrosion and require utilities to assess corrosion in their distribution and home plumbing systems. Problems caused by corrosion can be grouped into 3 categories: health, aesthetics and economics. Corrosion can be thought of as a gnawing away or an attack on a metal. It may be uniform and attack a surface evenly or it may cause severe localized problems such as a crevice or pit. For the corrosion reaction to proceed, all components of an electrochemical cell are required - an anode, a cathode, a connection between the anode and cathode and a conducting solution. Corrosivity is affected by many factors, including pH, alkalinity, dissolved oxygen, flowrate, temperature and others. Some factors can be controlled; others cannot. Corrosion occurs in the water treatment plant. The constant wetting and drying of certain treatment components and the corrosive chemicals used are causes for concern. The water quality served to the customer is a significant factor in corrosion and should be adjusted to make it reasonably non-aggressive. Methods for documenting corrosion range from simple visual inspections to complex scale analysis including weight loss and pitting depth measurements and corrosion probes. Laboratory and pilot tests can be used to define the extent and magnitude of corrosion. Corrosion control programs should be developed with a two-phased approach in mind - changing water chemistry and using corrosion resistant materials. Understanding the principles of corrosion is important in avoiding and correcting corrosion problems. Monitoring is important to ensure that the corrosion control program continues to meet its desired objective.

## INTRODUCTION

With the passage of the Safe Drinking Water Act, Public Law 92-523, in 1974; the Federal Government, through the U.S. Environmental Protection Agency (USEPA) began to deal in depth with providing safe drinking water for public use. While for the most part, water purveyors have provided safe, potable drinking waters to consumers for many decades, this new act required the establishment of first interim and then revised primary drinking water standards based on health-based contaminant levels.

In response to the Safe Drinking Water Act, the USEPA established the National Interim Primary Drinking Water Regulations (NIPDWR) in 1977, which in part established maximum contaminant levels for certain inorganic chemicals, including lead and cadmium. The NIPDWR further require that the maximum contam- inant levels be met at the consumer's tap. Previous regulations had been concerned only with water quality in the utility distribution system. Later USEPA established the National Secondary Drinking Water Regulations which suggested guidelines for iron, copper, and zinc. Finally, in recognition of the potential pickup of contaminants by the water as it travels through the distribution system and the premise plumbing, the USEPA has amended the NIPDWR to include "Corrosivity" as a requirement (Federal Register Vol. 45, No. 168/Wednesday, August 27, 1980/ Rules and Regulations, pp. 57332-57357).[1]

Briefly these amendments require the Utility to:

(1) Collect and analyze samples to determine the corrosivity characteristics of the water by monitoring the alkalinity, pH, calcium hardness, temperature, and total dissolved solids (TDS) of the water; also the Langlier Index must be calculated, and

(2) Determine the materials of construction in the distribution system including service lines and home plumbing systems.

Based upon this monitoring program, an initial determination as to the corrosion problem in a water system is to be made.

## PROBLEMS CAUSED BY CORROSION

A water supply that exhibits corrosive characteristics can cause problems in distribution pipelines and home plumbing systems. These problems can be grouped into three categories: Health, Aesthetic, and Economic.

### Health

Corrosion of plumbing and distribution system materials cause an increase in metal compounds in the water. Lead, cadmium and other heavy metals are present in various

amounts in system materials, and there is concern for the possible health hazards created by corrosion and subsequent leaching and ingestion of these materials. The presence of lead, even at low concentration, in the drinking water supply is of concern because of its toxic and commulative effect, especially in young children.

Aesthetics

Secondary contaminants that are primarily an aesthetic nuisance are also leached from the distribution system plumbing materials. These include copper, iron and zinc. These contaminants, when present in concentration above the suggested limits, can render the water aesthetically undesireable for consumption because of taste, color, or staining characteristics.

Economics

Corrosion also causes plugging and premature pipe failure. Plumbing and distribution system deterioration because of corrosion frequently results in extensive and costly plumbing replacement. Copper pipe corrosion is usually characterized by a uniform etching or thinning of the pipe wall. Failure occurs only when corrosion has so damaged the structural integrity of the pipe that leakage becomes a problem. Galvanized steel corrosion is normally characterized by pits which develop in the pipe surface. These pits may eventually penetrate the pipe wall and cause leakage. As the pipe deteriorates, tubercles build up over the developing pits. These tubercles tend to form a blockage in the pipe and can eventually so restrict the water flow that the pipe must be replaced. Internal corrosion of unlined cast iron water mains can cause higher pumping costs for the utility.

PRINCIPLES OF CORROSION

What is Corrosion? Before discussing the principles of corrosion, it would be well to define corrosion. The word itself is derived from the Latin "rodere" meaning "to gnaw". With this in mind, corrosion may be thought of as the gnawing away or attack on a material, usually by some chemical or electrochemical means. Corrosion has also been defined as "nature's way of taking from man what man has taken from nature".[2]

The process of taking from nature involves extraction of the ores from their environment and an eventual conversion into a usable metal. The manufacturing process usually requires high heat, during which process, all oxygen and moisture are removed. The finished product is a metal which is highly stressed and which contains a quantity of stored energy.

Burial in the ground or exposure to the atmosphere, where contact with oxygen and moisture are allowed, will trigger a release of the stored energy and allow corrosion to

take place. The metal will return to its original state as an ore.

How quickly the metal will corrode will depend on the amount of energy required to produce the product. Metals which require large amounts of energy usually corrode quickly while metals such as gold and silver, which are generally used in their original state, are resistant to corrosion.

## COMMON FORMS OF INTERNAL CORROSION

Internal corrosion occurs in several, widely differing forms. Classification is usually based on the appearance of the corroded metal and can either be uniform or localized.[3]

### Uniform Corrosion

Uniform corrosion occurs when the metal corrodes at approximately the same rate over its entire surface. Uniform attack usually results in an even thinning of the pipe wall, until the pipe can no longer hold up under the water pressure or external loads and, subsequently, structural failure occurs.

### Localized Corrosion

Localized corrosion occurs when the metal surface is attacked unevenly creating areas that are severely affected while adjacent areas may not be affected at all. Localized corrosion may be divided into galvanic, pitting, crevice and erosion corrosion.

Galvanic corrosion may occur when two dissimilar metal pipes are placed in direct or electrical contact. A difference in electrical potential exists between the two metals and this potential difference produces electron flow between them. Corrosion of the less corrosion-resistant metal is usually increased and attack of the more resistant material is decreased, as compared with the behavior of the metals when they are not in contact.

Galvanic corrosion can often be recognized by the increased amount of corrosion close to the junction of two dissimilar metal pipes. An example of this is when copper and iron pipe are joined together. This can be avoided by using dielectric insulators to separate the dissimilar metal pipes.

Crevice corrosion is intense localized corrosion that occurs within crevices and other shielded areas on pipe surfaces. This type of attack is usually associated with small volumes of stagnant solutions caused by holes, gasket surfaces, pipe joints, surface deposits and corrosion products. With time, the condition of the water in such crevices can become quite different from that of the free-flowing water. A more aggressive environment may

develop and cause local corrosion in the crevice. Crevice corrosion is usually attributed to one or more of the following changes which can occur in a crevice: Changes in pH, change in the oxygen concentration, build-up of an aggressive ion, or depletion of a corrosion inhibitor chemical.

Pitting corrosion is a form of localized attack that eventually results in holes in the metal pipe. Pits can be of various shapes and sizes, and the degree of attach can range from mild to very severe. The indentation that results from pitting is responsible for its continued growth, for the same reasons mentioned in the discussion of crevice corrosion. In actuality, a pit can be considered a self-formed crevice. Pitting usually requires an extended initiation period before visible pits appear, which depends both on the type of pipe and water quality. Once started, however, a pit penetrates the pipes at an ever increasing rate. The rapid penetration of the pipe wall and the development of pinhole leaks makes pitting one of the most destructive forms of corrosion.

When the high velocity movement of water through a pipe increases the rate of attack because of mechanical wear, the attack is called erosion corrosion. The corrosion is accelerated by localized removal of a protective corrosion film and the metal is removed from the pipe surface both as dissolved ions and solid corrosion products. Erosion corrosion is characterized in appearance by smooth-bottomed shallow pits which usually exhibit a directional pattern. It thrives on turbulent, high-velocity conditions and is frequently seen in bends and elbows of piping systems. (Example: Copper pipe is especially vulnerable at velocities 5fps, at 140 degrees F.)

## THE BASIC CORROSION REACTION

Electrochemical corrosion can be viewed from the standpoint of oxidation and reduction. For corrosion to occur, all the components of an electrochemical cell are required - an anode, a cathode, and a conducting solution (Figure 1). At the anode, the oxidation of a metal (M) to its ion occurs. Figure 1 also shows two possible anode reactions for corrosion in iron pipe.

At the anode, corrosion can be inhibited when the oxidation products form a stable solid such as an oxide, hydroxide, or carbonate that adheres to the pipe surface and prevents or slows direct contact between the metal and the corrosive water and thus provides a barrier to corrosion reactions. This is known as passivation. In the iron corrosion example shown in Figure 1, the compound or compounds that form depend on a number of factors, including pH and buffer capacity. Siderite, or $FeCO_3$, may form and show the corrosion rate. If conditions favor the formation of hydrous oxides of iron, such

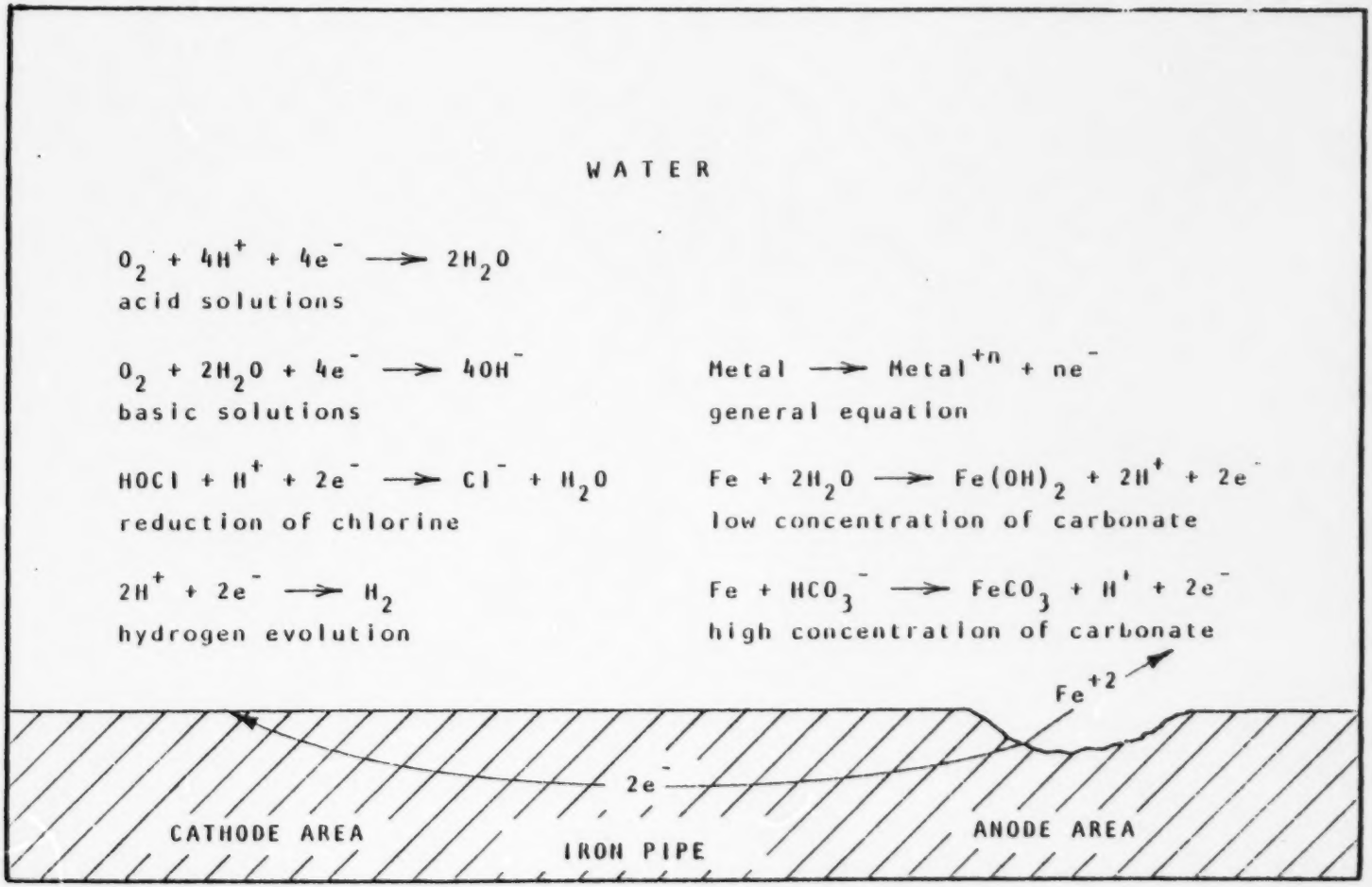
WATER
$O_2 + 4H^+ + 4e^- \longrightarrow 2H_2O$
acid solutions
$O_2 + 2H_2O + 4e^- \longrightarrow 4OH^-$
basic solutions
$HOCl + H^+ + 2e^- \longrightarrow Cl^- + H_2O$
reduction of chlorine
$2H^+ + 2e^- \longrightarrow H_2$
hydrogen evolution
$Metal \longrightarrow Metal^{+n} + ne^-$
general equation
$Fe + 2H_2O \longrightarrow Fe(OH)_2 + 2H^+ + 2e^-$
low concentration of carbonate
$Fe + HCO_3^- \longrightarrow FeCO_3 + H^+ + 2e^-$
high concentration of carbonate
$Fe^{+2}$
$2e^-$
CATHODE AREA
IRON PIPE
ANODE AREA

FIGURE 1. SOME ANODE AND CATHODE REACTIONS FOR IRON PIPE CONTACTING WATER

as $Fe(OH)_2$ and $Fe(OH)_3$, soft and porous coatings may not inhibit corrosion.

Electrons are transferred to the cathode when corrosion occurs, and a number of reduction reactions may occur here. Some are shown in Figure 1. The cathode reactions indicate that factors favoring corrosion include low pH (high concentration of hydrogen ion) and high concentration of oxidizing substances such as dissolved oxygen and free residual chlorine. Note also that after hydrogen ion is reduced to hydrogen gas, transporting the hydrogen gas away from the cathode area promotes continued corrosion.

## FACTORS AFFECTING THE CORROSIVITY OR DRINKING WATER[4]

pH. Low pH's generally accelerate corrosion.
Dissolved Oxygen. Dissolved oxygen in water induces active corrosion, particularly of ferrous materials.
Free Chlorine Residual. The presence of free chlorine in water promotes corrosion of ferrous metals and copper.
Low Buffering Capacity. Insufficient alkalinity to provide buffering capacity to the water and provide protective films.
High Halogen and Sulfate/Alkalinity Ratio. A molar ratio of strong mineral acids much above 0.5 results in conditions favorable to pitting corrosion.
Carbon Dioxide. Carbon dioxide is particularly corrosive to copper piping.
Total Dissolved Solids. Higher concentrations of TDS salts increase conductivity and may increase corrosiveness. Conductivity may be measured to obtain an estimate of TDS.
Calcium. Generally reduces corrosion by forming protective films with dissolved carbonate.
Silica. Forms protective films over metal surfaces.
Tannins. Form protective organic films over metals.
Flow Rates. Turbulence at high flow rates allows oxygen or $CO_2$ to more easily reach the surface, removes protective films and causes higher corrosion rates.
Metal Ions. Certain ions such as copper can aggravate corrosion of downstream materials. For example, copper ions can increase the corrosion of galvanized pipe.
Temperature. High temperature increases corrosion reaction rates. High temperature also lowers the solubility of calcium carbonate and calcium sulfate and thus may cause scale formation in hot water heaters and pipes.

## CORROSION OF IRON PIPE[3]

Iron pipe corrosion is characterized by pitting and the formation of iron oxide tubercles. Generally, unlined iron pipe life spans in low pH and alkalinity water are quite short. Failure can usually be attributed to plugging and pinhole leaks. The pitting and tuberculation process is initiated when, for any reason, the rate of iron dissolution is momentarily increased at particular points on the pipe surface. This usually occurs in a surface scratch, near surface irregularities, in standing

water, and near iron oxide deposits. Once initiated, pitting occurs by an autocatalytic process. That is, the corrosion processes within a pit produce conditions that are both stimulating and necessary for the continuing activity of the pit.

Within the pit, rapid dissolution of iron occurs and oxygen is depleted. Because iron dissolution continues, an excess positive change develops. This positive change is balanced by the migration of chloride and other ions into the pit to maintain electroneutrality. Thus in the pit there is a high concentration of $FeCl_2$ and as a result of hydrolysis,

$$FeCl_2 + 2H_2O \quad Fe(OH)_2(s) + 2H^+ + 2Cl^-$$

a high concentration of hydrogen ions. Both hydrogen and chloride stimulate the dissolution of iron and the entire process accelerates with time.

At the interface between the pit and the adjacent surface, iron hydroxide tubercles form because of the interaction between the $OH^-$ produced by the cathodic reaction and the dissolved iron.

$$Fe^{2+} + 2OH^- \quad Fe(OH)_2(s)$$

Dissolved oxygen can further oxidize the iron (II) hydroxide to $Fe(OH)_3$, $Fe_3O_4$, $Fe_2O_3$ and other oxides. This is evidenced by different colored layers in tubercle. Favorable conditions can result in formation of $FeCO_3$ and subsequent iron compounds that form a protective layer on iron pipe and inhibit corrosion. A discussion of the mechanism of corrosion inhibition by siderite formation has been presented recently in JAWWA by Sontheimer et al.[5]

## CORROSION OF GALVANIZED PIPE

Galvanized pipe deterioration occurs in two stages. Initially, only the galvanized or zinc layer corrodes until iron is exposed. Corrosion of the galvanized layer is very much dependent on pH, carbonate content, and flow.

Once the galvanized layer is penetrated and iron is exposed, the galvanized pipe begins to perform as an iron pipe. Initially, the zinc will sacrifically corrode, offering protection to the iron. Eventually, the iron base metal of the pipe begins to pit and iron oxide tubercles are formed. Soon the pipe must be replaced because of plugging or leaking or both.

## CORROSION OF COPPER PIPE[3]

The corrosion of copper pipe is generally of an even uniform nature. In the presence of dissolved oxygen, a thin cuprous oxide film is formed over most of the surface of the metal. This film promotes a constant corrosion rate

which is normally only a fraction of the corrosion rate of iron or galvanized pipe. However, pitting of copper pipe can occur. This is usually caused by a breakdown of the passivation film. The film can be disturbed by high velocity water, or dissolved by either carbonic acid or organic acids which are found in some fresh waters. Chlorides also tend to promote pitting by increasing the porosity of the passivation film. Chlorine increases the oxidation of copper and prevents the establishment or continuation of the protective cuprous oxide film.

Near the vicinity of a soldered joint, a galvanic couple is formed between the copper pipe and the solder. Here, the copper acts as the cathode and the solder as the sacrificial anode. In the case of 50/50 lead-tin solder, the principal anodic reaction is the dissolution of lead and the subsequent leaching of lead into the drinking water. The lead leaching problem is eliminated with the use of 95/5 tin-antimony solder. The principal reaction in the corrosion of the 95/5 solder is the passivation of tin, which inhibits metal leaching from the solder.

## CORROSION OF LEAD PIPE[3]

Lead pipe has been in service for many years in many older water distribution systems. Although it is durable for use in potable water, the toxic properties of trace amounts of dissolved lead should preclude its use in soft potable water.

The corrosion of lead pipe is very much dependent on pH and alkalinity. At very low alkalinities, lead is soluble throughout the drinking water pH range. In water containing carbonate alkalinity, an insoluble film of basic lead carbonate forms in the intermediate pH region. For example, at a total alkalinity of 20 mg/L and pH of 9.5, the concentration of lead in water circulating through lead pipe was below 50 ug in an EPA experiment.[6] This film performs two functions: by adhering to the metal surface, it forms a physical barrier between the metal and the water; and the basic carbonate or carbonate solid phase limits the lead solubility and therefore reduces the amount of lead which can be leached into the drinking water. It should be noted, however, that even in systems containing high pH values, corrosion can occur at very low and high alkalinities.

## CORROSION IN THE WATER TREATMENT PLANT[6]

Before discussing methods for monitoring and control of corrosion in plumbing and distribution systems, it might be well to look at corrosion in the water treatment plant. The potentials for deterioration are present from the raw water intake and lift station to the treated water storage tank. For example, because of repeated wetting and drying, intake screens and trash racks are subject to corrosion. Unusual flow patterns through

meters can erode pipe surfaces. Inlet weirs often consist of sharp edged metal plates. Sharp edges of steel members are well known to be areas of high stress. That high stress areas are more likely to corrode than less highly stressed areas is probably less well known.

Optimum pH for flocculation is often at corrosive pH levels. Metal in flocculation basins must be protected. Sedimentation basins are also subject to corrosion. Sludge may be abrasive. Sludge deposits can set up localized corrosion cells. Chemicals used in water treatment plants can present special problems - inorganic and organic coagulants are corrosive. Our commonly used disinfectants, chlorine and ozone are highly corrosive and require that special measures be taken to avoid corrosion.

Standard treatment techniques applied to potable waters can make them more aggressive to the materials commonly used in home plumbing and distribution systems. Use of alum decreases pH and increases sulphates. Use of gaseous chlorine and hydrofluosilicic acid also reduce pH and alkalinity and add chloride and fluoride to the water. There have been instances noted where bringing a filter plant on-line has caused significant corrosion related problems for customers because alum coagulation reduced pH and alkalinity.

## METHODS OF CORROSION MONITORING[8]

Utilities are responsible for both the integrity of the distribution system and the quality of the water served to their customer. Corrosion monitoring activities should be undertaken in ways that supply information about both the condition of the distribution system and the quality of tap water. Causes and effects of corrosion can be measured in many ways, ranging from simple visual observation of main taps to very complex analysis using the scanning electron microscope. These methods can generally be broken down into two broad categories for discussion purposes: (1) the water quality characteristics, and (2) the pipe material. Both an aggressive water and a susceptible piping material are necessary for corrosion to occur.

### Water Quality

Indices. Water utilities have been required for several years to analyze their water for parameters that can give an indication of a water's corrosiveness including: pH, alkalinity, hardness, calcium, and total dissolved solids. These parameters can be used to calculate corrosion indices and to compare with the corrosiveness of similar waters. Common indices include the Langlier Index (LI), the Ryznar Index (RI), the Aggressive Index (AI), and the Driving Force Index (DFI).[9] These indices have one common thread in that they all relate to the solubility of ca calcium carbonate. In certain types of waters they

may be valid but in the very soft waters of the Northwest and Northeast it may not be feasible to use the indices to control corrosion. Riddick developed a corrosion index on an empirical basis. It included carbon dioxide, hardness, alkalinity, chlorides, nitrates, dissolved oxygen and silica. These indices can provide some insight into the corrosive tendencies of a water supply.

Water Quality Changes in Distribution and Home Plumbing Systems.[4] To determine if corrosion is affecting the water quality in the transmission and distribution system, a base line water quality analysis survey of water as it enters the transmission lines from the source of supply must be completed and compared with analyses of samples collected at various locations within the distribution system. This survey should include variables such as different sources of supply, different pressure zones, secondary treatments within the distribution system, open reservoirs and different types of pipelines. The appropriate parameters should be analyzed based on the composition of the material being used. For example, if the transmission lines are of concrete cylinder or asbestos cement pipe and storage reservoirs are concrete, logical parameters are pH, alkalinity and calcium (or hardness). Analyzing for substances that may protect pipe, such as iron, manganese, and silica, would also be appropriate. The following summary lists parameters that are suggested for water quality analysis for different types of pipe material and includes substances that may increase corrosion, decrease corrosion, or be products of corrosion of the pipe in question.

| WATER MAIN MATERIAL | PARAMETER OF INTEREST |
|---|---|
| Ductile and Cast Iron (if cement lined) | -Iron, Manganese, Conductivity, Dissolved Oxygen, (DO), Color, pH. Also Alkalinity and Calcium if cement lined. |
| Steel | -Iron, Manganese, Conductivity, DO, Color, pH |
| Concrete Cylinder and Asbestos Cement | -pH, Alkalinity, Calcium, Conductivity, Iron Silica. Also asbestos fibers for asbestos cement. |
| Galvanized Steel | -Zinc, Cadmium, Lead, Iron, DO, pH, Color, Conductivity, Alkalinity. |

The above parameters are not a complete list of all components needing analysis under potential corrosion conditions but should indicate the rationale to be followed in selecting parameters for analysis. Changes in these quality parameters indicates corrosion of the material is occurring. Unfortunately, no easy method exists for determining the quality of water at the customer's tap except to sample there. Changes in quality parameters between "standing" and "running" water will normally indicate if corrosion is occurring in the home

plumbing system or in a service line. "Standing" samples are taken from water which has remained for an extended period of time (e.g., overnight) in a customer's plumbing system. They are the first flush of water from the plumbing system. "Running" samples are those collected from the customer's tap after any stale or "standing" water has been removed by a flushing of the system. It is generally the fresh, flowing water from the utility main. Many different water quality parameters have been analyzed for in previous tap studies. Between 4 and 20 constituents were monitored in metal surveys in Seattle, Boston and Oslo, Norway. The following table illustrates the divergence of metals monitored or screened in five separate surveys.

METAL PARAMETERS *10

| | Pb | Cd | Cu | Zn | Fe | Mn | Ni | Cr | Sn | Sb | Co | Ag | Hg | Al | Ca | Mg | Na | K |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Seattle, EPA Study | X | X | X | X | X | X | | | | | | | | | X | X | | |
| Seattle, Seattle Water Metals Survey | X | X | X | X | X | X | X | X | X | X | X | X | | | | | | |
| Seattle, National Heart and Lung Institute | X | X | X | X | | | | | | | | | | | | | | |
| Boston, EPA | X | X | X | X | X | X | X | X | | | X | X | | | X | X | | |
| Oslo, N.I.P.H. | X | X | X | X | X | X | X | X | | | X | | X | X | X | X | X | X |
| Community Water Supply Survey, USPHS | X | X | X | X | X | X | X | X | | | X | X | | | | | | |

As with the samples in the distribution and transmission system, the sampling program at the consumer's tap must address the various types of plumbing material. Most plumbing systems are a mix of several different types of pipe and this can make results of analysis difficult to interpret. Because knowing what type of plumbing is often difficult, a standard series of parameters should be analyzed for on each tap sample. Assuming that the standard types of pipe are in use, such as galvanized, black steel, copper or lead, the minimum quality parameters to be tested for should include Cd, Pb, Cu, Zn and Fe. Parameters of secondary interest include Mn, Sn, Al, Cr, Ni, Sb, pH, alkalinity and specific conductance.

Complaints and Questionnaires. Records of customer quality complaints should be kept in an orderly manner and should include the name, location, date, nature of complaint and the remedial action taken. Those records provide a good history of when changes made in the system have caused an increase or decrease in corrosion. An example would be a new water source or a treatment change. Although these records are a good indicator of the changes in corrosiveness, they do not necessarily document the extent of the problem. To determine the extent, a questionnaire sent to a random sample of customers is quite useful. Many customers do not call in about a particular problem but they may take five minutes to fill out a simple questionnaire.

Extent of Staining. The extent of staining can be a useful visual measure of corrosion, especially in comparing treatment methods. The water exiting treatment pipe loops can be discharged onto a white porcelain plate and the staining effects of different treatments compared. This is an inexpensive method and can be useful in presenting results of a pilot program to utility management.

## PIPE AND COUPON TESTING PROGRAM

After conducting the water quality sampling program, a suggested next step is to develop a field investigation program to gather pipe specimens for evaluation. Normally, gathering the pipe section or pipe taps is a relatively simple task but the evaluation is much more difficult. This section will discuss methodology which has been successfully used in the past for measuring corrosion and for developing pipe sampling and pilot testing programs.

### Methods of Analysis

Water utilities, the American Society of Testing Materials (ASTM) and the National Association of Corrosion Engineers have developed standard procedures for testing pipe coupons including visual observation, micrographs, weight loss, pitting potential, scale analysis and corrosion probes as outlined below:

Visual Inspection. Often times a visual inspection of the pipe is a good method of evaluation. It can be used to classify both the extent of tuberculation and sometimes the type of corrosion. For example, a galvanized pipe may be badly "tuberculated" with most of the interior area closed off due to rusting, or a copper pipe may be "etched" with "generally even" corrosion. Books with illustrations of different types of corrosion are available to help classify corrosion.

Micrographs. Electron microscopes have been used to view the interior portions of a pipe. For example, asbestos cement pipe may have asbestos fibers protruding from the surface as the cement bonding material is dissolved by an aggressive water. This method could possibly be used to compare the surface texture of new and old pipes.

Weight Loss. Because internal corrosion dissolves the metal pipe material, the weight of the pipe will decrease with time and this decrease can be measured. Tedious cleaning and weighing procedures must be followed, but this is one of the best procedures used for pilot and laboratory test comparisons of various water treatment processes and pipe materials.

Pitting Potential. Pitting corrosion (corrosion in which pit depths are $\geq$ 25% of pit widths) may cause pipe failure through penetration of pipe walls. The pit depths of test specimen and pipe sections can be measured with a

micrometer in many cases. The use of a microscope with a graduated fine focus adjustment is even more versatile in pit depth and width measurements. Calculations of "pitting rates" is valuable in predicting pipe lives for various materials and water conditions.

Scale Analysis. Analysis of the coating or scale found on a pipe wall is important because is may provide an indication as to why the pipe is protected or is deteriorating. For example, a high concentration of calcium or silica on the pipe wall could act as a barrier to the diffusion of oxygen and thereby reduce the corrosion rate. Scale analysis can also be used to determine the effectiveness of a treatment method designed to lay down a specific coating. Methods for the analysis may include X-ray fluorescence, X-ray diffraction, atomic absorption, emission spectroscopy, infra-red spectroscopy, and gravimetric methods.

Corrosion Probes. Probes are available that are designed to measure the corrosion rate of various metals and depending upon the water characteristics, they can be very useful. They are best used to follow short term changes in the corrosion rates of various water supplies and corrosion treatment without having to remove the test unit from source. As with weightloss, probe readings do not necessarily indicate what is happening in the field unnless they are verified by actual comparison with an existing pipe which has been in place for quite some time.

Field Sampling Program

Transmission and Distribution System. Several methods are available for sampling and evaluating the condition of the transmission and distribution system. If transmission lines are large, a walk-through inspection of certain sections would be worthwhile. Distribution reservoirs and tanks can also be investigated in this manner. In the distribution system, pipe taps and pipe sections being removed or repaired provide an excellent record of the condition of the system if the specimens are properly and accurately tagged and kept. The information should include who removed the pipe, where, why, condition upon removal, age, and other pertinent remarks. Meters and valves can also be inspected as part of the routine maintenance program. Utilizing methods mentioned earlier, such as visual inspection, weight loss, pitting depth and rate, scale analysis, head loss readings, and review of leak records, the extent of corrosion can be documented and the magnitude quantified.

Plumbing Systems. Most utility personnel are much more familiar with methods of evaluation in the distribution system than they are in home plumbing systems. Since the NIPDWR became effective in June of 1977, water quality degradation because of plumbing corrosion has been the utility's problem. To address this quality degradation

issue, corrosion of home plumbing systems indirectly becomes the purveyor's problem to solve. Contrary to the practice of most utilities who have selected corrosion-resistant materials for many years for use in their own distribution system; many builders, plumbers, contractors and home owners have not chosen corrosion-resistant materials to put in home and building plumbing systems. In many cases, the unlined metallic pipes are quite susceptible to corrosion, especially in the environment of the soft, acidic, low alkalinity, surface waters.

A home sampling program in which various pipe types of different ages are removed and evaluated is the best way to determine the condition of the customer piping. Evaluation methods include visual inspection, pittting potential and scale analysis. Questioning the home owner about possible low pressure problems can give an indication of the corrosive action of water on certain types of piping. Plumbing repair shops probably know the condition of home plumbing systems better than anyone and will usually share their knowledge with the utility. Most shops stockpile old pipe, hot water tanks, and other equipment before disposal and a visit to a couple of plumbing shops will provide a quick look at the problem areas. Based on this investigation, the typical service life of the various types of plumbing can be estimated and if desired, a cost can be placed on the deterioration of home plumbing systems caused by the aggressive action of the water.

Pilot Plant Program. Several methods are available for testing pipe coupons and evaluating the effectiveness of alternative treatment programs. Most of these involve exposing a piece of metal (or pipe section) to the water and then measuring the corrosion rate by weight loss or some other method after a given length of time. Metals initially corrode at very high rates and then slow down with time. Rates for some metals such as copper may stabilize within two or three months; whereas experience with galvanized pipe indicates that approaching steady state conditions may take more than a year. At least two methods of evaluation have been used with some degree of success - immersion, and Illinois State Water Survey (ISWS) (ASTM D2688- IDC) flow-through tests. The immersion test involves suspending metal coupons for various times (one to six months) to measure the resulting corrosion rates. Some investigators perform the tests on a batch type basis, others have a continuous flow of water through the container and some combine the two variations by simply changing the water periodically during the test period. The other method involves maintaining a continuous flow of water through lengths of actual pipe. New pipe sections are prepared and inserted into a pipe loop in such a manner that they can be removed at preset time intervals for evaluation. This seems to be a more reliable test method than immersion testing although it is much more tedious and time comsuming. The suggested testing period is six to twelve months or more in length.

Comparison of Field and Pilot Tests. In many cases, the results from field plumbing specimens do not correlate well with laboratory or pilot plant loop tests; thus, an actual comparison must be made before conclusions are drawn. Even if actual corrosion rates in the field do not correlate well with pilot tests, the pilot tests are still very valuable for making comparisons between various chemical treatment alternatives. Pilot tests can also be used to estimate service life of actual plumbing pipe under different chemical treatments. This can be accomplished using relative corrosion rates or a percent reduction in the corrosion rate based on pilot tests, and then applying the percent reduction to the pipe in the field. Carrying the analysis one step further, the relative corrosion rates from pilot plant tests can be used to estimate the costs or benefits associated with corrosion because of a new water source or a change in chemical treatment. Having this type of knowledge before a change in water quality is made is invaluable.

## COSTS OF CORROSION

The significance of corrosion costs to the overall U.S. economy has been recently reported by the National Bureau of Standards (NBS). Corrosion costs in the U.S. were estimated at $70 billion annually in 1975. The direct cost portion of this amount is approximately 25% which in proportion to the gross national product is 4.2%.[11] The proportion of costs that can be avoided by corrosion control measures is approximately 15% of the direct cost portion. The same NBS report indicated that the annual costs in the water supply field total approximately $700 million. These costs are only for distribution systems; however, often, a far greater portion of corrosion costs are incurred through damage to interior piping and plumbing systems. Replacing a water heater could cost the homeowner $200-300. The cost of replacing accessible plumbing in a home would be several hundred dollars. If all of the plumbing in a home has to be replaced, costs could easily reach $2,000 to $3,000.

Corrosion damage can be quantified in terms of dollars and cents and benefits of corrosion reductions can also be calculated. The general approach to such calculations is based on knowing the pipe life under existing conditions and then projecting pipe life if the water quality conditions change. By performing a present worth analysis and comparing monetary benefits of longer pipe life versus the costs of water treatment, a benefit to cost ratio can be calculated. A brief example follows:

Assuming under the present water quality conditions that the pipe life is 30 years in a single family dwelling and that the house is twenty years old. The pipe now has ten years of useful life until it either becomes so plugged with rust that neither flow nor pressure can be maintained at adequate levels. Interim repairs, leak damage and total replacement are assumed to occur as follows:

## SCHEDULE OF REPAIRS

| | | |
|---|---|---|
| Replace Service Line | 1982 | $ 300.00 |
| Interim Repair | 1987 | $ 75.00 |
| Leak Repair | 1989 | $ 100.00 |
| Leak Damage | 1989 | $ 150.00 |
| Replace Accessible Plumbing | 1992 | $1,000.00 |

If a treatment method is instituted that will reduce corrosion by 40%; the repairs, pipe damage, leaks and replacement will be put off to some point in the future. The following tables list present worth values of the corrosion damage with and without treatment.

PRESENT WORTH VALUES
WITHOUT CORROSION TREATMENT

| Item | Year | Cost | PWF (10%) | Present Worth |
|---|---|---|---|---|
| Replace Service Line | 1982 | $ 300.00 | 1.00 | $300.00 |
| Interim Repair | 1987 | $ 75.00 | .62 | $ 46.00 |
| Leak Repair | 1989 | $ 100.00 | .51 | $ 52.00 |
| Leak Damage | 1989 | $ 150.00 | .51 | $ 77.00 |
| Replacement | 1992 | $1,000.00 | .38 | $385.00 |
| | | | | $860. 00 |

WITH CORROSION TREATMENT

| Item | Year | Cost | PWF (10%) | Present Worth |
|---|---|---|---|---|
| Service Line | 1982 | $ 300.00 | 1.00 | $300.00 |
| Interim Repair | 1989 | $ 75.00 | .45 | $ 34.00 |
| Leak Repair | 1994 | $ 100.00 | .33 | $ 33.00 |
| Damage Repair | 1994 | $ 150.00 | .33 | $ 49.00 |
| Replacement | 1999 | $1,000.00 | .20 | $200.00 |
| | | | | $616. 00 |

These calculations indicate that the cost saving attributable to a 40% reduction in the corrosion rates will be $244 ($860-$616) over the life of the plumbing. Assume that treatment costs $0.05/1,000 gallons which is being very conservative on the high side, the present worth of these costs is $57.90. Thus, the benefit: cost ratio becomes $244 to $57.90 or 4.2:1. For every dollar spent the return is 4.20. This is considered a very beneficial ratio.

The cost aspect of corrosion is a very powerful tool to be used by the utility in presenting persuasive arguments for reducing corrosion damage. Manager and customers understand dollars and cents and this method of presenting data should be given serious consideration.

## DEVELOPING THE CORROSION CONTROL STRATEGY[12]

The Federal Regulations that require water quality monitoring and a survey of distribution materials are good starting points. Corrosion is a very complex, electrochemical phenomena that can seldom be totally eliminated. Normally, the utility can hope to reduce the problem to a more tolerable level by a two-phased approach: changing the water chemistry and selecting the most corrosion resistant materials for a particular water.

Changing the water chemistry should be based on laboratory and pilot tests. Benefits in terms of water quality and corrosion reduction should be documented. Several methods are available for changing the water quality including using chemical inhibitors and blending of more mineralized ground water with soft surface supplies. Chemical inhibitors can be effective, but their use is often opposed by the utility's customers. In addition, inhibitors can be quite expensive, especially those that require large amounts of energy for processing. Chemical inhibitors can also be used effectively at the point-of-use, expecially on hot water systems. Blending of water supplies is a good solution if the less corrosive water is available in the appropriate quantity and quality to effect the desired water quality change. Most utilities have not blended water for the purpose of controlling corrosion but have traditionally used the cheapest method of supply.

Coupled with the changes in water quality, a program that selects corrosion resistant materials is usually the best long term solution. Measures that have been used by some utilities include cleaning and cement lining pipelines; using stainless steel, brass, bronze or plastic materials; using plastic piping for service connections, changing plumbing codes to allow plastic piping in homes; using glass lined water heaters; and requiring the use of low lead solders in the plumbing and distribution system.

The methods described above are general in nature and must be tailored to the specific water quality and distribution system. Once a plan is implemented, a monitoring program should be continued to make certain the corrosion control program continues to work effectively.

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